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Superconducting property of $BaHfO_3$ doped $SmBa_2Cu_3O_y$ films prepared by alternating-targets technique on IBAD-MgO

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Abstract

In order to improve superconducting properties of REBCO films under magnetic fields, we fabricated BHO-doped SmBCO films on IBAD-MgO substrates by PLD method using alternating-targets technique which can change the content of the BHO in the SmBCO films. Consequently, T_cs and J_cs at self-field of the BHO-doped SmBCO films were decreased from 92 K to 89 K and 3.0 MA/cm^2 to 1.2 MA/cm^2 at 77 K in self-field with increasing the BHO content. However, J_c of the BHO-doped SmBCO films in high magnetic fields exceeded that of a pure-SmBCO film.

Keywords : $SmBa_2Cu_3Oy$; critical current density; $BaHfO_3$; ion beam assisted deposition (IBAD)-MgO; pulsed laser deposition; thin film; pinning force

1. Introduction

A $REBa_2Cu_3O_y$(REBCO, RE: rare earth elements) has been developed as a material for second generation of superconducting wire. For using the REBCO wire in high magnetic field applications such as magnetic resonance imaging (MRI), superconducting magnetic energy storage (SMES) and nuclear fusion reactor, it is necessary that the REBCO have a high critical current density (J_c) in magnetic fields. In order to improve critical current density under magnetic fields, an introduction of artificial pinning centers (APCs) into REBCO thin films is very effective. $BaMO_3$ (BMO, M=Hf, Zn Sn) is one of the APCs. It is well known that the BMO is grown into a form of nanorod along the *c*-axis direction of a REBCO. Therefore it shows a strong pinning force in magnetic fields applied parallel to the *c*-axis direction of REBCO thin films. Our group have previously fabricated BZO, BSO and BHO-doped $SmBa_2Cu_3O_y$ (SmBCO) films on single crystalline substrates [1-4]. J_cs in magnetic fields of the BZO or BSO doped SmBCO films were improved however T_c and J_c in self-field were decreased. On the other hand, J_cs in magnetic fields of the BHO-doped SmBCO films were higher than that of the BSO or BZO doped SmBCO films. Furthermore T_c and J_c in self-field did not decrease so much. In addition, to use the REBCO film for superconducting applications, it is necessary that depositing REBCO films on metallic substrates. Our group have fabricated thick SmBCO films on IBAD-MgO substrates by using low-temperature growth (LTG) technique in order to enhance I_c in magnetic fields [5].

In this study, we fabricated BHO-doped SmBCO films on IBAD-MgO substrates aiming to use for the high magnetic field applications and we changed BHO content to control the number density and the size of BHO nanorod.

2. Experimental procedure

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We deposited the SmBCO thin films on CeO_2/LMO/IBAD-MgO/GZO/Hastelloy substrates (IBAD-MgO) by pulsed laser deposition (PLD) method with a KrF excimer laser (λ=248nm). The substrate temperature was fixed to 940 ˚C. The laser energy density was 2.0 J/cm^2 and repetition frequency is 10 Hz. The distance between target and substrate was 70 mm. The partial pressure of oxygen was 0.4 Torr during the deposition. We used alternating-targets (ALT) technique to introduce BHO into SmBCO. In the ALT technique, two or more targets are repeatedly exchanged to obtain a desired composition. We changed BHO content in the SmBCO films easily by using the ALT technique with the targets of SmBCO and BHO. A number of pulses to the SmBCO target was fixed at 80 pulses and that to the BHO target was changed to 5, 12, 16, and 24 pulses. In the cases, the BHO content in the films were 0.40, 0.95, 1.27, and 1.91 vol.%, respectively. The crystal structure and the crystallinity of the SmBCO films were analysed by X-ray θ-2θ diffraction. The thickness and the atomic composition of the films were analysed by inductively coupled plasma emission spectrometry. The J_c and T_c values were measured by DC four-probe method with a physical property measurement system (PPMS).

3. Results and discussion

A pure-SmBCO film and all the BHO-doped SmBCO films showed *c*-axis orientation and cube-on-cube in-plane texture. Fig. 1 (a) shows the BHO content dependence of the T_c. T_c of the pure-SmBCO film was 92.6 K and that of the 1.91 vol.%-BHO-doped film was 88.8 K. T_c of the BHO-doped SmBCO films decreased with increase of the BHO content. A similar tendency has also seen in BSO or BZO doped YBCO films on $SrTiO_3$ single crystalline substrates [6, 7]. However, T_cs of the BHO-doped SmBCO films on $LaAlO_3$ substrates were not decreased, even if increase of the BHO content. Fig. 1 (b) shows the *c*-axis length as a function of the BHO content. First, the *c*-axis length of the BHO-doped SmBCO films was longer than that of the pure-SmBCO film on MgO substrate. The *c*-axis length of the pure-SmBCO film on MgO substrate is 11.73 angstrom [1]. Additionally, the *c*-axis length of got longer with increase of the BHO content. The *c*-axis length of the BHO-doped SmBCO films on $LaAlO_3$ substrates showed similar tendency. As the reason of this elongation, the oxygen vacancy and strain between SmBCO phase and BHO phase are considered. The *c*-axis length depends on the oxygen vacancy [8] and increases with increasing the oxygen vacancy. It is well known that the oxygen vacancy effects on T_c considerably. However, in this work, since we introduced the oxygen into the SmBCO films before these measurements by post O_2-anealing, we considered that the oxygen vacancy did not increase. On the other hand, the strain between SmBCO phase and BHO phase are caused by the difference of their lattice constants. The *c*-axis length of SmBCO is three times longer than that of BHO. So that one SmBCO unit cell (UC) would nearly correspond to the three BHO UCs. However *c*-axis length of the one SmBCO UC and that of the three BHO UCs are 11.76 angstrom and 12.51 angstrom, respectively. Therefore, the *c*-axis length of the SmBCO phase would be elongated by the BHO. Based on this mechanism, we considered that the *c*-axis length of the SmBCO increased with increasing the BHO content due to the strain between SmBCO phase and BHO phase.

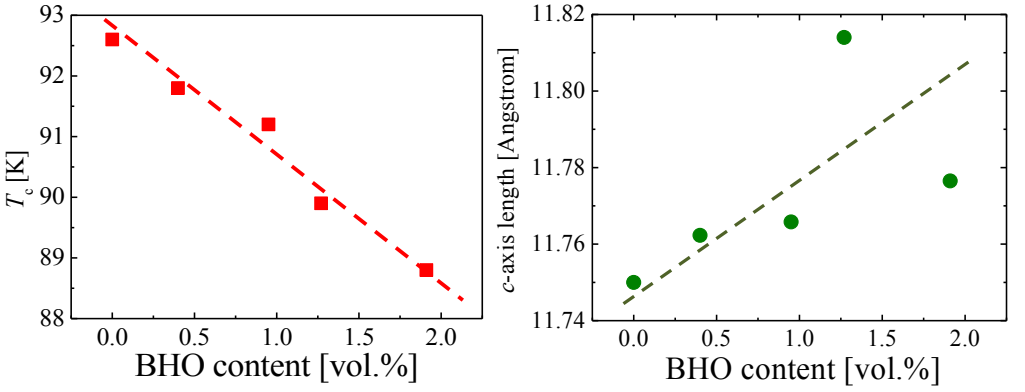

Fig. 1. (a) Decreasing of the T_c and (b) *c*-axis length of the SmBCO films doped various BHO content

Fig. 2 shows the measurement temperature dependence of the irreversibility field of the BHO doped SmBCO films. The 0.40 vol.% and 0.95 vol.%-BHO-doped SmBCO films did not show the significant pinning effect. In these films, BHO particles would be formed and the particles could be too small amount. Then the BHO particles could not become effective pinning centers. In contrast, the 1.91 vol.%-BHO-doped SmBCO film showed a remarkable pinning effect in magnetic fields from 0.5 T to 3.0 T, namely, there was two kinks on the irreversibility line. Similar structure is reported in many reports, for example, in ref. [1] and this is almost common property of the vortex system with *c*-

axis-correlated pinning centers. The irreversibility field at 77 K of the 0.40 vol.% and 0.95 vol.%-BHO-doped SmBCO films was higher than that of the pure-SmBCO film. The value of the pure-SmBCO film was 7.18 T and that of the 0.40 vol.% and 0.95 vol.%-BHO-doped SmBCO films were 7.81 T. However, the irreversibility field of the 1.91 vol.%-BHO-doped SmBCO film was decreased to 7.06 T. It is considered that T_c of the 1.91 vol.%-BHO-doped SmBCO film is significantly decreased.

Fig. 3 shows magnetic field dependences of J_cs for the field applied parallel to the *c*-axis of the films. The pure-SmBCO film typically showed J_c~3 MA/cm^2 in self-field. At high magnetic fields of more than 2.5 T, J_c increased with increasing the BHO content. However J_cs of the 0.40 vol.% and 0.95 vol.%-BHO-doped SmBCO films were similar to J_c of the pure-SmBCO film in the fields more than 2 T. As mentioned above, it is considered that the BHO particles do not act as effective pinning centers in the BHO-doped SmBCO films. In the case of the films with the BHO content of more than 1.27 vol.%, J_cs of the BHO-doped SmBCO films exceeded that of the pure-SmBCO film. For example, J_c of the 1.91 vol.%-BHO-doped SmBCO film was about three times larger than that of the pure-SmBCO film. In addition, from Fig.3, the J_c curve of 1.91 vol.%-BHO-doped SmBCO film had a plateau from 0.5 T (P_{start}) to 2.5 T (P_{end}). It is considered that this plateau is due to the pinning effect. In high magnetic field, interaction between the flux quanta is strong. When there are strong pinning centers, it is suppressing the decline of J_c, even if the flux quanta increase.

The maximum pinning force (F_p^{MAX}) of the pure-SmBCO film is 3.7 GN/m^3 in 1.7 T, and that of the 0.95 vol.% and 1.91 vol.%-BHO-doped SmBCO films were 6.3 GN/m^3 in 1.7 T and 5.7 GN/m^3 in 3 T, respectively. F_p^{MAX} was improved by doping the BHO into the SmBCO films. The magnetic fields that showed F_p^{MAX} were sifted to higher magnetic field with increase of the BHO content. The reason is a number of the PC was increased.

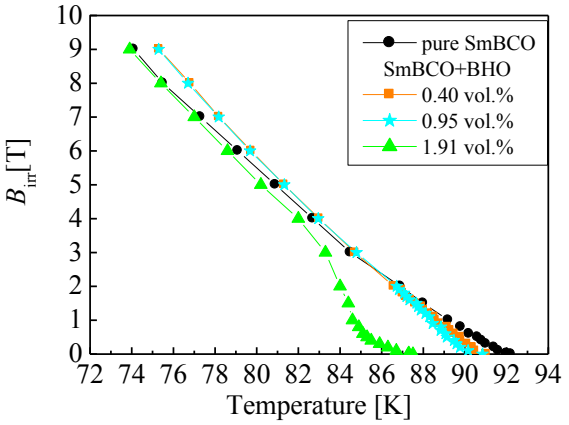

Fig. 2. Irreversibility field as a function of temperature of the BHO-doped SmBCO films

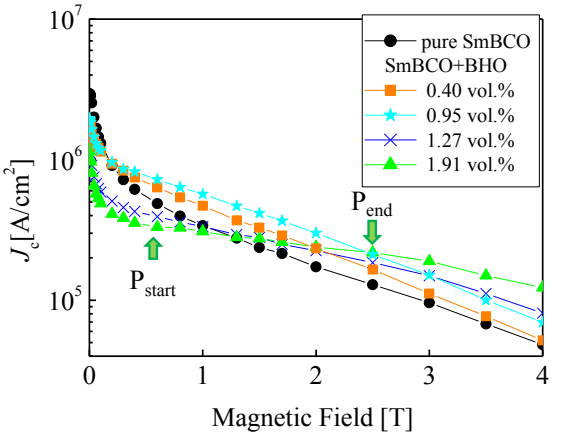

Fig. 3. Magnetic fields dependence of J_c for the fields applied parallel to the *c*-axis of the BHO-doped SmBCO films

Fig. 4 shows the magnetic field angular dependence of normalized J_c which was divided by J_c in the magnetic field applied parallel to the *ab*-plane of the SmBCO films and the 1.48 vol.%-BHO-doped $GdBa_2Cu_3O_y$ (GdBCO) film [9]. The normalized J_c of 0.95 vol.%-BHO-doped SmBCO film increased for all angles of applied magnetic field compared with that of the pure-SmBCO film. Thus, the BHO was introduced randomly and affected as the three-dimensional pinning centers in the 0.95 vol.%-BHO-doped SmBCO film. This result is consistent with the discussions in Figs. 2 and 3. In contrast, the normalized J_c of 1.91 vol.%-BHO-doped SmBCO film significantly increased in magnetic field applied parallel to the *c*-axis of the film. This means that the BHO in the film grown into a form of nanorod and also supposes the result of Fig. 2. From these results, when the BHO content is not enough, the BHO in the film does not grow into the form of nanorod. The first possible reason is that growth rate of the BHO nanorods is too slow. In this case, since the SmBCO would overlie the BHO nanorods during the growth, the BHO did not continuously grow along the *c*-axis direction of SmBCO film. The second possible reason is that atoms composing the BHO nanorods are too little. When the atoms diffuse on the surface, it is difficult to reach BHO nuclei which are formed by aggregation of previous atoms and then the non-coalesced atoms re-evaporate. Therefore, under the condition in this work, BHO would not be formed nanorod below 0.95 vol.% of BHO.

We compared J_c of the 1.91 vol.%-BHO-doped SmBCO film with that of the 1.48 vol.%-BHO-doped GdBCO film. The J_c peak around *B*//*c* in the 1.91 vol.%-BHO-doped SmBCO film was sharper than that of the BHO-doped-GdBCO film. Since the substrate temperature of the BHO-doped SmBCO films (940 ˚C) was higher than that of the BHO-doped GdBCO film (850 ˚C), the BHO in the SmBCO film would grow up straightly compared with that in the

GdBCO film. We have reported that straightness of BZO nanorods in the SmBCO film is improved with increasing the substrate temperature [1]. Therefore, it is considered that the BHO nanorods also show the same tendency.

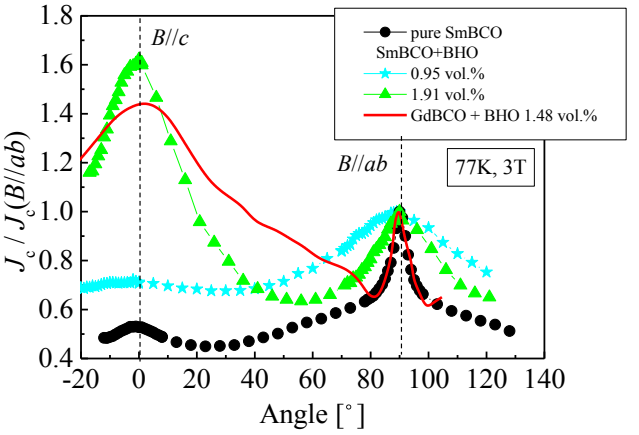

Fig. 4. Magnetic field angular dependence of normalized J_c divided by J_c in magnetic field applied parallel to the *ab*-plane of the SmBCO films doped various BHO content

4. Conclusion

We fabricated the BHO-doped SmBCO films on IBAD-MgO substrates by alternating-targets technique. J_c in magnetic fields of more than 1T increased due to the BHO doping. In particular, J_c of the 1.91 vol.%-BHO-doped SmBCO film was 0.19 MA/cm^2 in 3T. This value was three times larger than that of the pure-SmBCO film in 3T. If the BHO content was less than 0.95 vol.%, the BHO-doped SmBCO film would include weak pinning centers with a three-dimensional shape. On the other hand, if the BHO content was over 1.91 vol.%, the BHO grew into the form of nanorod. The J_c of the SmBCO thin films on IBAD-MgO substrates were enhanced by introducing the BHO, and were improved with increasing the BHO content. However, T_cs of the BHO-doped SmBCO films decreased with increasing the BHO content. In the future, further improvement of the J_c in high magnetic fields is expected by introducing the BHO in a way that does not decrease the T_c.

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